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The effects of arms and countermovement on vertical jumping

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ABSTRACT

HARMAN, E. A., M. T. ROSENSTEIN, P. N. FRYKMAN, and R. M. ROSENSTEIN. The effects of arms and countermovement on vertical jumping. *Med. Sci. Sports Exerc.*, Vol. 22, No. 6, pp. 825–833, 1990. Countermovement and arm-swing characterize most jumping. For determination of their effects and interaction, 18 males jumped for maximal height from a force platform in all four combinations of arm-swing/no-arm-swing and countermovement/no-countermovement. For all jumps, vertical velocity peaked 0.03 s before and dropped 6–7% by takeoff. Peak positive power averaged over 3,000 W, and occurred about 0.07 s before takeoff, shortly after peak vertical ground reaction force (VGRF) and just before peak vertical velocity. Both countermovement and arm-swing significantly ($P < 0.05$) improved jump height, but arm-swing's effect was greater, enhancing peak total body center of mass (TBCM) rise both pre and posttakeoff. Countermovement only affected the post-takeoff rise. The arm-swing resulted in higher peak VGRF and peak positive power. During countermovement, the use of arms resulted in less unweighting, slower and less extensive TBCM drop, and less negative power. Countermovement increased pretakeoff jump duration by 71–76%, increased average positive power, and yielded large positive and negative impulses. High test-retest reliability was shown for jump descriptive variables. Body weight together with peak posttakeoff TBCM rise effectively predicted peak power (multiple $R^2 = 0.89$, standard error of estimate = 243 W). The results lend insight into which jumping techniques are most appropriate for given sports situations and indicate that a jump test can effectively be used to estimate peak power output.

HUMAN POWER OUTPUT, FORCE PLATFORM, SPORT TECHNIQUES, STRETCH-SHORTEN CYCLE, IMPULSE, NEGATIVE POWER, ECCENTRIC EXERCISE

Vertical jumping contributes in varying degrees to performance in most sports. Jumping is usually preceded by a countermovement, which can be described as a quick bend of the knees during which the body's center of mass drops somewhat before being propelled upwards. Enoka (3) reported a 12% jump height advantage with the countermovement among a group of 44 subjects. The countermovement uses the stretch-shortening cycle in which eccentric muscle stretching stores elastic energy, which is in part released during immediately subsequent concentric muscle contraction. There is some evidence that individuals with predominantly fast twitch muscle fibers are better able to recover stored elastic energy in high speed countermovement jumps with less knee angular displacement, while individuals with predominantly slow twitch fibers can recover more stored elastic energy in slower jumps involving greater knee angular displacement (1). The ability to recover stored elastic energy may be affected by previous training as well (4).

It has been theorized that improvement in performance with the countermovement may in part result from potentiation, during the eccentric stretching phase, of myoelectric activity during the subsequent concentric contraction phase. However, contribution of such a mechanism appears unlikely because integrated EMG amplitude has been shown to be no greater during vertical jumps with a countermovement than without one (2).

An additional theory proposed to explain the performance-enhancing effects of the countermovement is that a concentric contraction immediately following an eccentric stretch begins with the muscle already under considerable tension, making more chemical energy available for generation of force (3). The existence of such a mechanism has not been directly tested by experimentation.

Even though it leads to higher jumping, countermovement cannot always be effected before a vertical jump. In some sports situations, an athlete is already in a squatting or semi-squatting position before jumping. Also, when jumping in response to the movement of another athlete or a ball, a player may not have time to perform a countermovement.

Vertical jumps are often characterized by swinging of the arms. Luhtanen and Komi (5) measured the impulse produced during no-countermovement jumps using only one body part at a time and found a 10% contribution from the arms to takeoff velocity. Payne (6) reported that the use of arms superimposed one extra late peak onto the ground reaction force curve produced by leg and body action and ensured that the center of gravity was as high as possible before flight began (about 12% higher with arms than without). The author also stated that the arms produced "extra force for the propulsion of the body" resulting in a 5% (7.6 cm) greater jump height. A lower starting position noted for the jump without arms possibly was a confounding factor.

In sports it is not always possible to use the arms to assist in vertical jumping. An athlete might be precluded from swinging the arms, because they are occupied in throwing or manipulating a ball or other implement. The arms might have to be held in a raised position to prepare for blocking or catching a ball.

In none of the previous studies have the use of arms and countermovement been examined together. Because both are recognized as important factors in jumping, it would seem important to know how they interact with each other. The present study was undertaken to accomplish this goal. In addition, it was intended that close examination of more jump variables than in previous studies, including those describing the timing of various subevents of a jump, would provide information that would aid in selection of the most advantageous jumping techniques for given sports situations.

METHODOLOGY

The experiment was conducted in accordance with the policy statement of the American College of Sports Medicine (*Medicine and Science in Sports*, 10:ix–x, 1978) and U.S. Army regulation AR 70–25 on use of volunteers in research which require that human subjects give free and informed voluntary consent before participation.

Eighteen physically active male subjects (height: 179 ± 5.4 cm; body mass: 74.7 ± 7.7 kg; age: 28.5 ± 6.9 yr (mean ± SD)) jumped maximally from a force platform four different ways in random order: arms with countermovement (AC), arms with no countermovement (ANC), no arms with countermovement (NAC), and no arms with no countermovement (NANC). The subjects performed three trials of each type jump for a total of 12 jumps. None of the subjects had previous experience in the different jump types other than what they would have gained while engaging in common sports activities. Each subject was carefully instructed in how to perform the different types of jump and was allowed enough supervised practice to comfortably perform them within the specified constraints. It generally took three to five practice jumps at submaximal effort before the subject and experimenter felt a jump-type was being performed correctly. Less practice was required for the AC jump, apparently because it was most "natural." NANC jumps required the most practice because subjects had to control their tendencies to use arms and countermovement. Subjects rested between jumps until they felt no residual fatigue, usually between 1–3 min. The starting position for all countermovement jumps was an upright posture with the arms down at the sides (Fig. 1). For the AC jumps, the subject swung his arms back while letting his body drop and his knees bend, then jumped up as high as possible while swinging the arms in a downward, forward, upward arc. For the NANC jumps, the subject held his arms down at his sides while letting his body drop and his knees bend, then jumped up as high as possible while keeping his arms at his sides. For the ANC jump, the subject first assumed the knees-bent, arms-back position and upon command from the experimenter jumped vertically as high as possible while swinging the arms in a downward, forward, upward arc. For the NANC jumps, the subject assumed the knees-bent, arms-down position and upon command from the experimenter jumped vertically as high as possible while keeping his arms at his sides. For all jumps, the degree of knee-bend utilized by the subjects was self-determined, with the primary goal to jump as high as possible. No attempt was made to directly measure or control degree of knee-bend.

All jumps were performed on a model LG6-1-1 0.6 by 1.2 m force platform connected to a model SGA6-3 amplifier system, both from AMTI (Newton, MA). The output signal representing vertical ground reaction force (VGRF) was fed into a Hewlett-Packard (Lexington, MA) 310 microcomputer via an Infotek (Anaheim, CA) model AD200 12-bit analog-to-digital converter board sampling at 500 Hz. A computer program calculated values for variables describing the jumps. Data files from all the individual jumps were transferred to a VAX 780 mainframe computer (Digital Equipment Corp., Maynard, MA), where they were combined into one large file containing the data from all subjects.

Force platform information was used to generate curves of vertical position and velocity of the total body center of mass (TBCM) during each jump. The calcu-

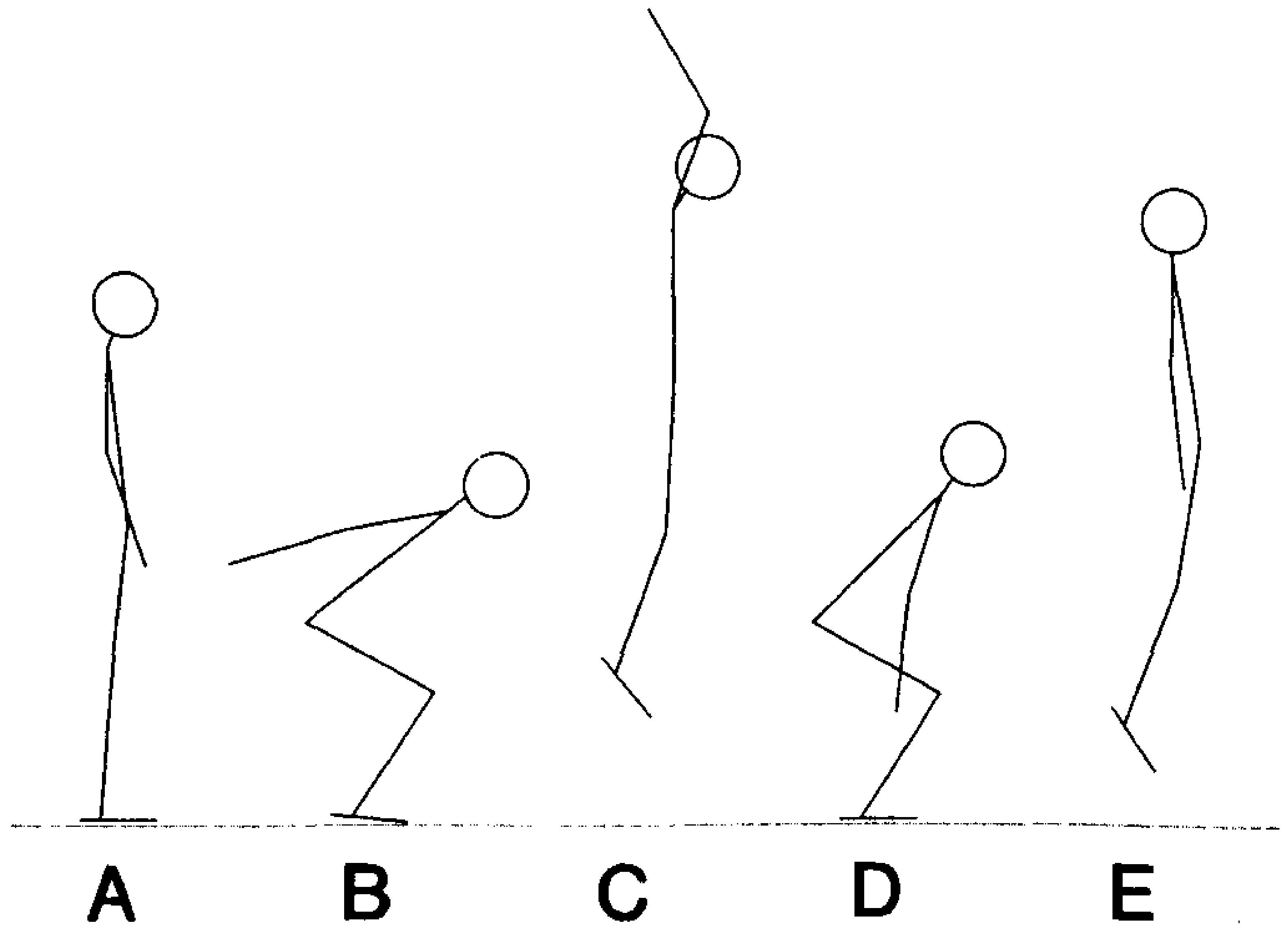

Figure 1—Sequences for the four types of jump: arms/countermovement = A,B,C; arms/no countermovement = B,C; no arms/countermovement = A,D,E; no arms/no countermovement = D,E.

lations were based on the principle that impulse equals change in momentum, or force multiplied by time equals change in the product of mass and velocity. Thus, for a jumper, change in TBCM vertical velocity during each sampling interval equals net external vertical force acting on the body multiplied by the time period over which the force is applied divided by body mass. The net force was taken as the VGRF reading from the force platform minus body weight. The change in velocity was calculated for each 500th of a second. Absolute velocity at the end of each interval was determined by adding the velocity change over the interval to the pre-interval absolute velocity, which was zero at the start of the jump. The position change over each interval was calculated as absolute velocity multiplied by the interval time. Position changes were added to yield absolute TBCM vertical position at the end of each interval. Instantaneous power was calculated as VGRF times the concurrent velocity of the TBCM. Maximum vertical displacement attained by the TBCM after takeoff was calculated from takeoff velocity using standard formulas for projectile motion (3).

Test-retest reliabilities of the descriptive variables over the three trials of each jump-type were measured using the SPSS (Chicago, IL) RELIABILITY program. A three-way repeated measures ANOVA was performed on all dependent variables using the BMDP (Los Angeles, CA) 2V program, where the three factors were (a) arms/no-arms, (b) countermovement/no-countermovement, and (c) trial. Correlations between different variables were performed using the BMDP 8D program. In order to determine if power output during jumping could be effectively predicted from jump height and body weight, multiple linear regressions were performed using the BMDP 1R program.

RESULTS

Table 1 shows Cronbach α reliability scores for variables identified by the authors as being most important in describing a jump. Almost all the variables showed excellent test-retest reliability. The few that didn't can be readily explained. By definition, during the no-countermovement jumps, peak negative TBCM displacement was minimal or nonexistent (Table 2) and thus not at all reliable. By the same token, peak negative power showed only fair-to-poor reliability for the no-countermovement jumps. During jumping, negative power occurs only when the TBCM is moving downwards while VGRF on the feet is directed upwards. The NANC jump was supposed to involve no TBCM downward movement at all, while the ANC jump was supposed to result in only small TBCM downward movement due to swinging of the arms downward from their up-and-back starting position. It turned out that both no-countermovement jumps evidenced some negative TBCM displacement and negative power, but of much smaller magnitudes than for the countermovement jumps.

TABLE 1. Test-retest reliabilities of the jump measures.

Variable Event	Cronbach's α			
	NC		C	
	NA	A	NA	A
Peak − TBCM displacement	−0.376	−0.311	0.944	0.958
Peak + TBCM displacement	0.956	0.961	0.983	0.988
+ VGRI	0.995	0.993	0.994	0.989
− immediate pretakeoff VGRI (Ns)	0.786	0.912	0.982	0.962
Net VGRI	0.994	0.992	0.995	0.996
Peak + TBCM velocity	0.989	0.986	0.993	0.994
Takeoff velocity	0.989	0.987	0.993	0.994
Minimum VGRF	0.963	0.989	0.937	0.899
Peak VGRF	0.977	0.965	0.986	0.983
Peak + power	0.992	0.983	0.993	0.989
Peak − power	0.570	0.744	0.983	0.970

$N = 18$.
A = arms, NA = no arms, C = countermovement, NC = no countermovement.
Positive (+) = upwards, negative (−) = downwards.
VGRF = vertical ground reaction force, TBCM = total body center of mass, VGRI = vertical ground reaction impulse.

The ANOVA showed that trial number produced no significant effects on the dependent variables, indicating that neither practice nor fatigue influenced the jumps over the three trials of each type. This does not negate the possibility that practice or training over an extended period of time would improve performance in any or all of the jumps. Due to the lack of a trial effect, means reported in the tables were calculated using data from all three trials under each condition.

Vertical travel of the TBCM during a jump can be broken down into two segments. The first is the rise of the TBCM from its location in the pre-jump position to its location just as the feet leave the ground. The second is the rise of the TBCM after takeoff. It is evident that technique translates to jump height in two ways: (a) by determining height of the TBCM at takeoff, and (b) by affecting pretakeoff net vertical ground reaction impulse (VGRI), which directly impacts upon takeoff velocity and in turn, posttakeoff TBCM rise.

Peak pretakeoff TBCM rise (Table 2) could not be directly compared between the countermovement and no-countermovement jumps, because the former jump began in a standing position, while the latter began in a lower, knees-bent position. However, use of the arms significantly ($P < 0.05$) increased peak pretakeoff TBCM rise because of its effects on body mass distribution. Because displacements were only measured relative to the *starting* position (which was not a standing position for the no-countermovement jumps), the effect of countermovement on peak pretakeoff TBCM rise above standing height could not be directly examined. Yet, it seems unlikely that the countermovement would have affected body geometry at takeoff or the resulting

TABLE 2. Descriptive variables for the four jump types.

Event	Significant Main Effects		Mean ± SD			
			NC		C	
	A	C	NA	A	NA	A
Peak − TBCM displacement (cm)	*	*	− 1.2 ± 0.9	− 1.4 ± 0.9	−35 ± 6.7	−32 ± 6.2
Peak + TBCM displacement (cm)	*	*	71 ± 11	81 ± 12	41 ± 8	52 ± 9
Average − power (W)	*	*	−9 ± 9	−12 ± 11	−417 ± 101	−374 ± 102
Average + power (W)		*	1260 ± 371	1337 ± 339	1450 ± 436	1470 ± 351
Peak pretakeoff TBCM rise (cm)	*	#	43.3 ± 7.0	47.7 ± 7.3	12.2 ± 1.6	16.9 ± 1.8
Peak posttakeoff TBCM rise (cm)	*	*	27.4 ± 6.6	33.2 ± 7.9	29.1 ± 7.4	35.3 ± 8.4
+ VGRI (Ns)	*	*	186 ± 25	205 ± 28	281 ± 47	289 ± 48
− countermovement VGRI (Ns)	*	*	−1.3 ± 1	−2.6 ± 3	−91.2 ± 25	−81.7 ± 25
− immediate pretakeoff VGRI (Ns)	*		−13.1 ± 2.9	−12.4 ± 2.8	−13.0 ± 3.0	−12.1 ± 2.8
Net VGRI (Ns)	*	*	172 ± 25	190 ± 28	177 ± 27	195 ± 28
Peak − TBCM velocity ($m \cdot s^{-1}$)	*	*	−0.02 ± 0.02	−0.03 ± 0.04	−1.21 ± 0.27	−1.07 ± 0.28
Peak + TBCM velocity ($m \cdot s^{-1}$)	*	*	2.47 ± 0.26	2.70 ± 0.28	2.54 ± 0.28	2.77 ± 0.29
Takeoff velocity ($m \cdot s^{-1}$)	*	*	2.30 ± 0.28	2.53 ± 0.30	2.37 ± 0.31	2.61 ± 0.32
Minimum VGRF (N)	*	*	717 ± 63	700 ± 84	263 ± 125	342 ± 126
Peak VGRF (N)	*		1562 ± 219	1687 ± 205	1697 ± 308	1725 ± 218
Peak + power (W)	*		3262 ± 626	3804 ± 684	3216 ± 607	3896 ± 681
Peak − power (W)	*	*	−13 ± 17	−22 ± 27	−1208 ± 469	−1050 ± 437

Displacements are relative to starting position, which was lower for the countermovement jumps.
$N = 18$, * $P < 0.05$.
# = not a meaningful comparison (countermovement jumps started lower).
A = arms, NA = no arms, C = countermovement, NC = no countermovement.
+ = upwards, − = downwards.
VGRF = vertical ground reaction force, TBCM = total body center of mass, VGRI = vertical ground reaction impulse.

pretakeoff TBCM rise above standing height. In future experiments, force plate data will be collected while the jumper is standing upright before assuming the knees-bent no-countermovement position. This will allow comparisons between countermovement and no-countermovement jumps in peak pretakeoff TBCM rise relative to standing height.

For each jump, peak positive TBCM displacement (or total TBCM rise above its starting position) equaled the sum of the pre and posttakeoff TBCM rises. The peak pretakeoff TBCM rise was about 4.5 cm higher with than without the arms. Because the TBCM traveled further from starting position to takeoff in a no-countermovement jump, the advantage in pretakeoff TBCM rise attributable to the arms amounted to 10% for the no-countermovement jump and 39% for the countermovement jump.

Both the arms and countermovement had significant positive effects on peak posttakeoff TBCM rise. Use of the arms had the greater effect, enhancing net VGRI by 10%, yielding increased takeoff velocity, and increasing peak posttakeoff TBCM rise by 6 cm, or 21%. The countermovement increased net VGRI by only about 3%, and peak posttakeoff TBCM rise by 2 cm, or 6%. The lower percentage increase for net VGRI than for peak posttakeoff TBCM rise is because the former is directly proportional to takeoff velocity, while the latter is related to the square of takeoff velocity, $((1.1)^2 = 1.21$ and $(1.03)^2 = 1.06)$.

While arm-swing enhancement of total jump height (peak positive TBCM displacement) resulted from increasing both peak pretakeoff TBCM rise and net VGRI, improvement through countermovement was probably attributable only to the latter. The arm-swing resulted in a 10–11 cm advantage for peak positive TBCM displacement, which translates to 14% and 27% for the no-countermovement and countermovement conditions, respectively. It should be noted that the latter percentage is more relevant to most sport situations, where the height one can jump above a standing, not a semi-squatting, position is usually most important.

As the countermovement jumps were initiated, ground reaction force dropped below body weight (Fig. 2). The degree of unweighting can be calculated as the percentage drop from subject bodyweight (733 ± 76 N) to minimum VGRF (Table 2). Unweighting during the countermovement was greater if the arms weren't used, when the VGRF dropped to a mean 36% of bodyweight. When the arms were used, VGRF only dropped to a mean of 47% of body weight. For the countermovement jumps, peak negative TBCM velocity was significantly greater when the arms weren't used. Apparently, the upward/backward swing of the arms partially offset the downward acceleration of the non-arm body mass.

The arm-swing caused the body to drop a mean of 3 cm less during the countermovement, as shown by peak negative TBCM displacement (Table 2). Film analysis of the jumps would have been necessary to determine how much of that was due to the higher position of the arms at the bottom of the countermovement in the AC

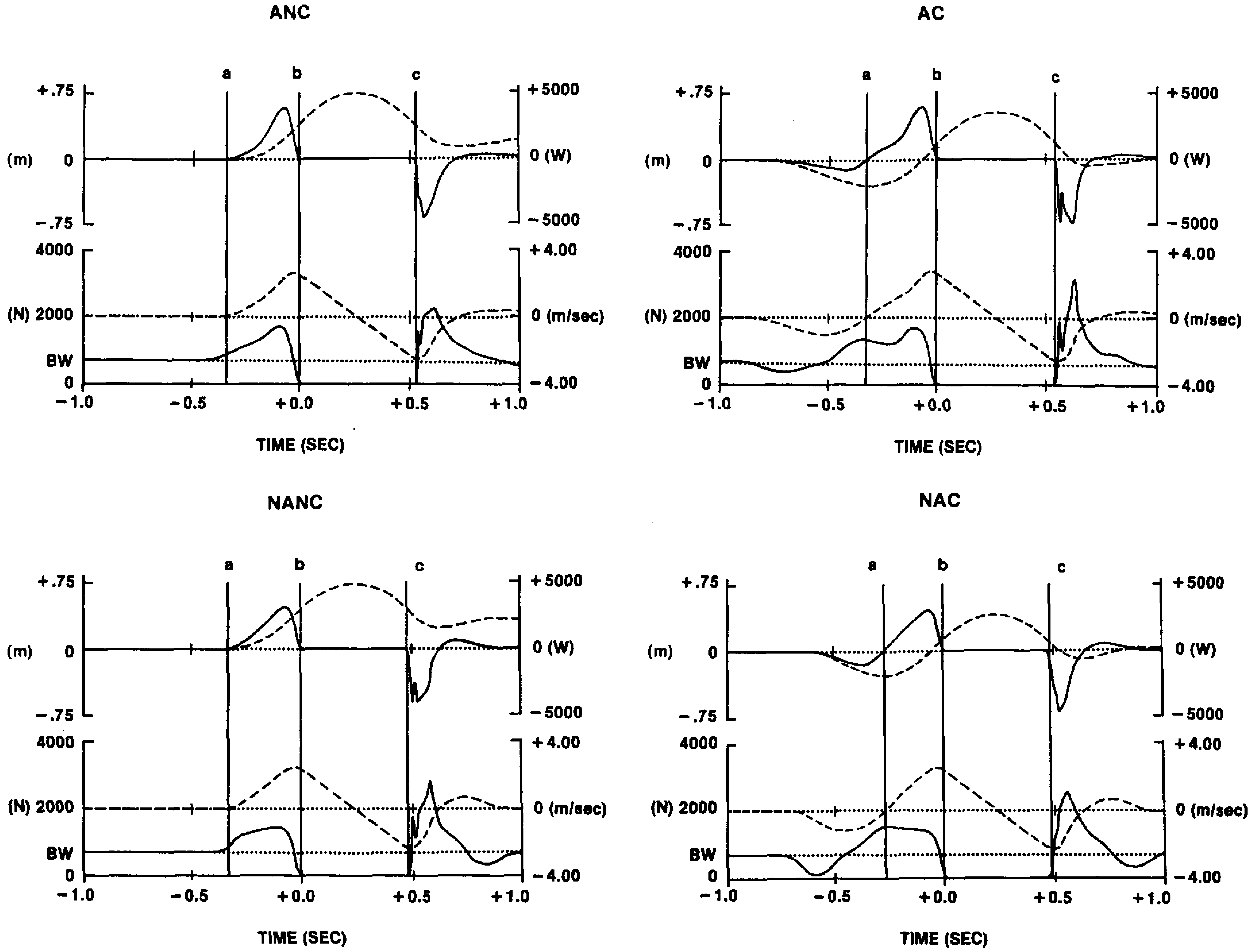

Figure 2—The lower graph for each of the four jumping conditions shows VGRF (*solid*) and TBCM vertical velocity (*dashed*). The upper graphs depict power output of the VGRF (*solid*) and TBCM position (*dashed*). *Vertical lines*: a = start of TBCM upward movement; b = loss of foot contact with ground; c = resumption of foot contact with ground.

than the NAC jumps, and how much, if any, was due to an effect of arm use on the extent of knee flexion or on movement of the trunk, head or other body segment.

Small countermovement during the no-countermovement jumps, which was not visually observable, was shown by minimum VGRFs that were slightly below body weight. It appears that, even with practice, most subjects could not completely eliminate countermovement. It was observed that even slight movements of the head and trunk could account for small amounts of unweighting, even when the knees showed no countermovement at all. Some of the unweighting during the ANC jumps can be explained by the initial downward acceleration of the arms from their up-and-back starting position.

The graphs portraying the countermovement condition (Fig. 2) show the TBCM back at its starting position after the jumps. With no countermovement, the TBCM ended up higher than where it started because the jumpers began with bent knees and stood fairly erect after completing the jumps.

Peak VGRF was significantly greater when the arms were used than when they were not (Table 2). Countermovement didn't show a significant effect on peak VGRF, but there was a greater effect of arms during jumps without (+8%) than with (+2%) countermovement which showed up as statistical interaction. During the NAC jumps, peak VGRF occurred when the TBCM was at its low point, probably because the type of jump was associated with relatively high peak negative TBCM velocity during the countermovement, requiring high forces to slow TBCM descent. For the other jumps, peak VGRF occurred closer to takeoff.

Peak positive TBCM velocity (Table 2) paralleled the differences in jump height among conditions. It should be noted that peak positive TBCM velocity did not occur at takeoff, but consistently 0.03 s before takeoff (Table 3). It appears that during the last 30 or so ms

TABLE 3. Times (s) of events relative to takeoff in approximate order of occurrence (negative times indicate pretakeoff).

Event	Significant Main Effects		Time of event(s)			
			NC		C	
	A	C	NA	A	NA	A
First movement		*	−0.50 ± 0.13	−0.50 ± 0.09	−0.82 ± 0.12	−0.86 ± 0.12
Minimum VGRF		*	−0.50 ± 0.10	−0.50 ± 0.10	−0.66 ± 0.11	−0.70 ± 0.12
First VGRF above body weight		*	−0.44 ± 0.11	−0.46 ± 0.10	−0.50 ± 0.08	−0.52 ± 0.08
Peak − pretakeoff TBCM velocity		*	−0.44 ± 0.10	−0.46 ± 0.09	−0.50 ± 0.08	−0.52 ± 0.08
Peak − power			−0.44 ± 0.10	−0.44 ± 0.09	−0.43 ± 0.08	−0.45 ± 0.08
Peak − TBCM displacement	*	*	−0.35 ± 0.07	−0.38 ± 0.06	−0.31 ± 0.05	−0.32 ± 0.04
Peak VGRF	*	*	−0.13 ± 0.06	−0.11 ± 0.02	−0.26 ± 0.08	−0.15 ± 0.10
Peak + power			−0.07 ± 0.01	−0.07 ± 0.01	−0.07 ± 0.01	−0.07 ± 0.01
Peak + TBCM velocity	*		−0.03 ± 0.006	−0.03 ± 0.006	−0.03 ± 0.006	−0.03 ± 0.006
Peak + TBCM displacement	*	*	0.24 ± 0.03	0.26 ± 0.03	0.24 ± 0.03	0.27 ± 0.03
Landing	*	*	0.48 ± 0.06	0.53 ± 0.07	0.50 ± 0.07	0.55 ± 0.07

$N = 18$, * $P < 0.05$.

A = arms, NA = no arms, C = countermovement, NC = no countermovement.

Positive (+) = upwards, negative (−) = downwards.

VGRF = vertical ground reaction force, TBCM = total body center of mass, VGRI = vertical ground reaction impulse.

before takeoff the large muscles around the hip and thigh had already contracted fully, leaving only the plantar flexors in position to continue to generate VGRF. However, based on the force-velocity relationship (7) and the speed at which they were contracting, these muscles probably could not exert force equivalent to body weight, and the TBCM actually decelerated, so that takeoff velocity was only about 93% of peak velocity.

Table 3 reveals the sequence of jump events, some of which can also be observed in Figure 2. "First movement" was when a jump began. It can be seen that the countermovement jumps took 71–76% longer from initial movement to takeoff than did the jumps without countermovement. For the countermovement jumps, it took about 16 ms from initiation of movement till maximum unweighting (minimum VGRF), at which time the jumper began to exert forces to decelerate his descent. These decelerative forces exceeded bodyweight some 16–18 ms later and downward (negative) TBCM velocity began to slow from its peak level. For the no-countermovement jumps, peak negative velocity and peak negative power virtually coincided, while for the countermovement jumps, peak negative power occurred about 7 ms later than peak negative velocity. The next event was peak negative TBCM displacement, when descent was finally brought to a halt. Peak VGRF occurred after the TBCM began to move upwards, and peak positive power was attained somewhat later, but before peak positive TBCM velocity.

Takeoff velocity is a direct function of both net VGRI (area under the VGRF vs time curve) and body mass. Thus it is not surprising that arms and countermovement affected net VGRI, just as they did takeoff velocity and peak posttakeoff TBCM rise (Table 2). The countermovement was associated with large positive VGRI, but also with sizable negative VGRI that canceled out a good portion of the positive one, so that the countermovement had a relatively small but significant positive effect on net VGRI.

Peak positive power averaged well over 3,000 W overall and close to 4,000 W for the AC condition. Only the use of the arms had a significant enhancing effect on peak positive power. In contrast, only the countermovement had a significant enhancing effect on average positive power. By definition, the muscles generated negative power when TBCM velocity and VGRF were opposite in sign, as when the body's rate of descent was slowed by VGRF during the latter part of the countermovement. During the countermovement jumps, both peak and average negative power were significantly greater when the arms weren't used. This is consistent with the greater unweighting and peak negative (downward) TBCM velocity for the no-arm jumps. Times of occurrence of power peaks were relatively consistent across jumps (Table 3), with the negative and positive peaks respectively occurring about 440 and 70 ms before takeoff. Because positive power is the product of positive TBCM velocity and VGRF, it is not surprising that peak positive power generally occurred between peak positive TBCM velocity and peak VGRF.

The identification of variables most closely associated with jump height was accomplished through statistical correlation (Table 4). Peak pretakeoff TBCM rise, being mainly a function of subject height, did not correlate well with any of the variables describing important aspects of jump technique and is not listed in the table. Taller subjects could get their TBCMs higher in absolute terms before their feet left the ground, irrespective of force, impulse, and power patterns manifested. There were correlations, in the 0.3–0.5 range, of pretakeoff TBCM rise with both positive and net VGRI, but they probably reflect the tendency for taller subjects to be heavier and somewhat stronger. Table 4 shows correlation coefficients, many of which fall in the fair-to-

TABLE 4. Correlations of selected variables with peak posttakeoff TBCM rise.

	Correlation coefficient (r)				
		No Countermovement		Countermovement	
Variable	All Jumps	No Arms	Arms	No Arms	Arms
Peak + power	0.88	0.84	0.86	0.86	0.91
Net VGRI	0.83	0.82	0.80	0.82	0.79
Time of peak + power	0.68	0.82	0.69	0.78	0.66
+ VGRI	0.51	0.76	0.78	0.61	0.60
Average + power	0.54	0.57	0.56	0.59	0.49
Peak VGRF	0.49	0.35	0.49	0.53	0.49

$N = 18$.

All correlations were significant ($P < 0.01$).

Positive (+) = upwards, negative (−) = downwards.

VGRF = vertical ground reaction force, TBCM = total body center of mass, VGRI = vertical ground reaction impulse.

good range, for technique variables vs peak posttakeoff TBCM rise. Correlation coefficients relating the technique variables to peak positive TBCM displacement were somewhat lower and more dispersed through the poor through good range and are therefore not shown in the table.

The correlations show that average power, in contrast to peak power, is not reflected well by peak posttakeoff TBCM rise. This is probably because average power is greatly affected by total time taken to execute the jump movement. The time can be lengthened or shortened by slowing down or speeding up parts of the movement preceding the important high power phase that occurs within the last 150 ms of the jump.

The fair correlations between peak posttakeoff TBCM rise and time of peak positive power can be explained by higher jumps being faster, with all jump stages temporally closer to takeoff. The fact that the correlation coefficients for net VGRI vs peak posttakeoff TBCM rise were only good and not excellent reflects the fact that the TBCM rise is dependent not only upon net VGRI but on body mass as well. Positive VGRI didn't relate as well to jump height as did net VGRI, because positive VGRI can be offset at least in part by negative VGRI. Peak VGRF didn't correlate very well with jump height, because power is more relevant than force to jump height and power generation requires concurrence of high force and high velocity.

The very good correlations of peak positive power with peak posttakeoff TBCM rise suggested that the latter variable would be a good predictor of peak power. This was particularly true for the AC condition, which represented the more natural type of jump. Because force is a component of power, an attempt was made to predict peak power from body weight (gravitational force) and peak posttakeoff TBCM rise using multiple linear regression with the latter two independent variables specified. For all the jump types together the following equation produced peak power (P) estimates in watts from peak posttakeoff TBCM rise (R) in cm and body weight (W) in newtons (multiple $R^2 = 0.89$, standard error of estimate = 243 W):

$$P = 77.3R + 3.72W - 1598.$$

For the AC or "natural" jumps, the following regression-derived equation was developed to predict peak power (multiple $R^2 = 0.92$, standard error of estimate = 199 W):

$$P = 73.9R + 3.29W - 1122.$$

It would be convenient to be able to estimate peak power from total jump height, which is easily measured using a jump-and-reach test. For the no-countermovement jumps, regression equations using body weight and total jump height, as represented by peak positive TBCM displacement, could only produce correlation coefficients in the range of 0.7. However, for the countermovement jumps, peak power could be predicted from peak positive TBCM displacement (D) in cm and body weight (W) in newtons using the following regression-derived equation (multiple $R^2 = 0.93$, standard error of estimate = 199W):

$$P = 65.3D + 3.08W - 1759.$$

DISCUSSION

The high test-retest reliabilities of a great majority of the variables descriptive of jumping technique indicate consistency of both the measurement method and individual jump technique. The method appears to be acceptable for research into both jumping and human power output.

The arms contributed a mean 10% to takeoff velocity in the present experiment for both the countermovement and no-countermovement conditions, a proportion very similar to the effect reported by Luhtanen and Komi (5) in an experiment in which no-countermovement jumps were performed using either the whole body or individual body parts alone. Jump heights in the present study were similar to those reported by Enoka (3), but his subjects showed a 4 cm countermovement effect compared with the 2 cm one reported here. The most likely reasons for the discrepancy are differences between the subject populations and/or experimental methods. Enoka's results were reported in a textbook, without the detail required for a careful analysis of the experimental differences.

Readers must be cautioned that peak positive TBCM displacement, used in the equation developed to predict peak power, is not necessarily the same as jump height determined with the widely used jump-and-reach test. In the jump-and-reach test, the subject has the fingertips marked with chalk. While standing flatfooted with a wall at one side, the subject reaches up with the arm closest to the wall and marks it with the fingertips.

Then, from a standing or squatting position, the subject jumps as high as possible, placing another fingertip mark on the wall with the same hand. Jump height is taken as the vertical distance between touch locations. A subject usually thrusts both arms upwards during the jump-and-reach test but often thrusts the nontouching arm downwards while reaching up with the other arm to touch the wall. Although the jump-and-reach score should be similar to peak positive TBCM displacement, the former's use in the regression equation would likely produce less accurate estimations of peak power.

In order to estimate how closely mean jump-and-reach scores matched peak positive TBCM displacement, the same subjects were brought back a few weeks after the initial testing to perform a jump-and-reach test in which arms and countermovement were used. The mean jump-and-reach score was 46.9 ± 8.5 cm compared with 52.2 ± 9.4 for the total TBCM rise. The fact that jump-and-reach scores were less than TBCM rise distances was probably because (a) in the test, the low and high wall marks were both made with the arm in the overhead position, so that the score didn't reflect the rise of the TBCM attributable to the arm moving from the down to the overhead position before takeoff; and (b) touching a wall during a jump is more restrictive than jumping straight up into the air and possibly detracts from jump height. Even though they were performed more than a month apart, the two jump measures showed a correlation coefficient of 0.92. The high correlation suggests that an additional regression equation could be derived to effectively estimate peak power from a jump-and-reach score and body weight. The best way to produce information to develop such an equation would be to have subjects perform jump-and-reach tests from a force platform so that actual power production could be directly measured.

One might question how the arm-swing increases VGRI. The obvious answer is that upward acceleration of the arms must be accompanied by concomitant force at the feet. However, observations of the jumpers show that in most cases the arms decelerate relative to the rest of the body as they approach the fully raised position *before* takeoff, thus reducing VGRI. The fact that the arms return to zero vertical velocity relative to the rest of the body before takeoff means their *net* effect on VGRI should be about zero. How then does the arm-swing increase net VGRI? The answer appears to be in the force-velocity relationship of muscle contraction (7). When the muscles crossing the hip and knee are in the most advantageous position to exert VGRF, the upward acceleration of the arms creates a downward force at the shoulders on the rest of the body. This slows the contraction of the large quadriceps and gluteal muscles to velocities at which they can exert more force. Pretakeoff positive VGRI thus increases. When the arms decelerate near the end of their swing, they pull up on the rest of the body, making the quadriceps and gluteals contract at a more rapid speed which diminishes their force generation capability. However, this occurs when the knees and hips are almost fully extended, and the muscles around them aren't in position to generate much positive VGRF anyway. This mechanism is probably important in many sports techniques: acceleration of body parts not directly exerting force on the ground in order to slow down contraction of muscles most directly involved with external force application, thus allowing the latter muscles to contract more slowly and exert higher force when they are in an advantageous position.

It would be incorrect to conclude that because the use of arms and countermovement positively affect jump height they should both always be employed in sports involving jumping. In sports like high-jumping and long-jumping, where an athlete wants to get every last centimeter out of a jump, the use of both arms and countermovement is clearly called for. On the other hand, countermovement jumps take considerably longer to perform and result in only modest performance gain. Thus, there are many sports situations in which it is preferable to jump without a countermovement. Often, in basketball, volleyball, or other team sport in which jumping plays a major part, it is well worth sacrificing 2 cm in jump height in order to make a reactive movement more quickly. In a rebounding situation in basketball, an athlete might position himself with bent knees, trying to anticipate the direction in which the ball will bounce off the rim or backboard, then leap in the right direction at the appropriate time. If the highest 2 cm of the athlete's jumping potential is not needed in order to reach the ball, then the no-countermovement jump provides a clear advantage in movement time.

There are sports situations in which an athlete is precluded from using the arm swing for jumping because the hands are occupied by an implement or ball. Even when the hands are free, the best alternative is not always to use the arm swing. For example, when an athlete must reach up on very short notice to intercept a basketball pass or to block a volleyball spike, the hands can reach the ball most quickly if they start in the up position and, on cue, go directly to the ball without going down for the swing. That is true, of course, only if the athlete can jump high enough to reach the ball without the arm swing. Thus there are tradeoffs with the arm swing just as there are for the countermovement.

The quantitative information on jumping technique provided in this paper can assist coaches and athletes in determining the kinds of jump most effective for given sports situations. The peak power estimation equations can lead to the development of effective and easy to use maximal power output tests.

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